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# SEMIEMPIRICAL METHOD OF DETERMINING FLOW COEFFICIENTS FOR PITOT RAKE MASS FLOW RATE MEASUREMENTS

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## SUMMARY

Pitot rakes are often used to measure mass flow rate in circular or annular ducts. Often the rakes are area weighted and a simple summation is used to determine the average velocity. Errors in flow rate measurement are inherent in this technique because of the discretization of the velocity profile. The error decreases as the number of tubes on the rakes increases, and resolution of the velocity profile improves. A study was conducted to determine the error in measuring mass flow rate with pitot rakes in an annulus. The ideal flow rate was determined by using a unique semiempirical analysis for fully developed, turbulent flow. The velocity profile obtained from this analysis was imposed on the pitot rake, and an area-weighted summation was used to determine the flow rate that the rake would indicate. Results in terms of flow coefficient, or the ratio of ideal to indicated flow rate, ranged from 0.903 for one probe placed at a radius dividing two equal areas to 0.984 for a 10-probe area-weighted rake. Flow coefficients were not a strong function of annulus hub-to-tip radius ratio for rakes with three or more probes.

## INTRODUCTION

The measurement of airflow rate is of primary interest in the testing and development of aircraft propulsion systems. Several methods of measuring flow rate are available including choked-exit devices, venturis, and bellmouths. These methods generally require the installation of additional hardware for the specific purpose of measuring flow rate. Where installation of such hardware is impractical, other means of measuring flow rate must be devised. For inlet testing there is usually an array of total pressure rakes at the diffuser exit station to measure total pressure recovery and distortion. Such rakes are generally area weighted and may also be used to measure flow rate. Each ring (probe in each rake at a common radius) in the array is assigned an area of the circular or annular duct. If the rakes are area weighted, these are equal areas. This area combined with the measured ring total pressure, a representative static pressure, and the total temperature can be used to calculate a mass flow rate for that ring. Subsequent summation of all ring flow rates results in an estimate of the total mass flow rate. Because of the discrete nature of the measurements significant error exists in the indicated value of flow rate, especially in high velocity gradient regions such as boundary layers. Obviously the larger the number of probes on the rakes, the finer the resolution of the velocity profile and the smaller the error. To account for this discrepancy between the measured and ideal flow rates, experimentally determined flow coefficients applicable to a particular rake geometry and annulus hub-to-tip radius ratio have normally been used (ref. 1). However,

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since the flow coefficient varies with the number of probes on the rakes and the hub-to-tip radius ratio of the annulus, a semiempirical procedure for determining an applicable flow coefficient would be desirable in many cases.

This investigation was conducted to determine the error in the rake mass flow rate measurement for turbulent flow in an annulus due to the discretization of the velocity profile and the variation of this error with the number of probes on an area-weighted rake. Also investigated was the effect of annulus hub-to-tip radius ratio on the error.

A semiempirical method for determining the velocity profile in fully developed, turbulent flow in an annulus is presented. The integral of this velocity profile is compared with summation of velocities as measured by an area-weighted rake subjected to the same velocity profile. Results are presented as flow coefficients, or the ratio of the integrated profile to the summed, for area-weighted rakes of up to 10 probes and a range of annulus hub-to-tip radius ratios.

#### SYMBOLS

$A_i$	area assigned to probe $i$ , $m^2$
$A_n$	integration constant for region $n$
$B_n$	constant for region $n$
$C_F$	flow coefficient
$C_n$	constant for region $n$
$D_n$	constant for region $n$
$E_n$	constant for region $n$
$F(n)$	function of region $n$
$F(x)$	function of variable $x$
$I$	number of probes on rake
$K_n$	dimensionless distance from origin to inner radius of region $n$ , $r/R_t$
$K_n'$	dimensionless distance from hub surface to inner radius of region $n$ , $(r - R_h)/(R_t - R_h)$
$m_n$	ratio of turbulent to laminar viscosity in region $n$
$N$	number of regions in semiempirical method
$p$	static pressure gradient in flow direction, $Pa/m$
$r$	distance from origin in radial direction, $m$

$R_h$	annulus hub radius, m
$R_t$	annulus tip radius, m
$u$	dimensionless distance from origin in radial direction, $r/R_t$
$v$	velocity in z-direction, m/sec
$v_{max}$	maximum velocity in z-direction, m/sec
$v_n$	velocity in z-direction at interface of regions $n$ and $n - 1$ , m/sec
$\mu^{(l)}$	coefficient of laminar viscosity, Pa sec/m <sup>2</sup>
$\mu^{(t)}$	coefficient of turbulent viscosity, Pa sec/m <sup>2</sup>
$\tau_{rz}^{(l)}$	laminar transport of z-momentum in r-direction, Pa/m <sup>2</sup>
$\tau_{rz}^{(t)}$	turbulent transport of z-momentum in r-direction, Pa/m <sup>2</sup>

#### Subscripts:

$h$	hub surface
$i$	individual probe on rake
$N$	outermost region in semiempirical method
$n$	individual region in semiempirical method
$r$	radial direction
$t$	tip surface
$z$	axial direction

#### Superscripts:

$(l)$	laminar
$(t)$	turbulent

### APPROACH

#### Derivation of Semiempirical Velocity Profiles

To develop the turbulent velocity profiles, a semiempirical approach is used under the following assumptions:

- (1) Two-dimensional (axisymmetric) flow
- (2) Steady, fully developed flow

- (3) Incompressible flow
- (4) Linear pressure gradient in flow direction

Figure 1 depicts the flow situation and the coordinate system. The time-smoothed z-component of the momentum equation under the preceding assumptions becomes

$$p = \frac{1}{r} \frac{d}{dr} \left[ r \left( \tau_{rz}^{(l)} + \tau_{rz}^{(t)} \right) \right] \quad (1)$$

Before equation (1) can be integrated to yield velocity profiles, an additional equation is needed to relate the laminar and turbulent flux of z-momentum in the radial direction to the radial velocity gradient. To develop this relation, the annular cross section is divided into an arbitrary number of annular regions  $N$ . Within each region it is assumed that the negative of the radial velocity gradient is proportional to the sum of the laminar and turbulent momentum fluxes. Further the constant of proportionality in a particular region  $n$  is the sum of the laminar viscosity and a turbulent viscosity that varies from region to region. In equation form

$$\tau_{rz}^{(l)} + \tau_{rz}^{(t)} = - \left( \mu^{(l)} + \mu_n^{(t)} \right) \frac{dv}{dr} \quad (2)$$

Expressed in terms of the ratio of turbulent to laminar viscosity, which is constant in a particular region  $n$ , equation (2) becomes

$$\tau_{rz}^{(l)} + \tau_{rz}^{(t)} = - \mu^{(l)} (1 + m_n) \frac{dv}{dr} \quad (3)$$

where

$$m_n = \frac{\mu_n^{(t)}}{\mu^{(l)}} \quad (4)$$

Combining equations (1) and (3), there results for a region  $n$

$$p = - \frac{1}{r} \frac{d}{dr} \left[ r \mu^{(l)} (1 + m_n) \frac{dv}{dr} \right] \quad (5)$$

Integrating over the radial direction yields after rearrangement

$$\frac{dv}{dr} = - \frac{1}{\mu^{(l)} (1 + m_n)} \left( \frac{pr}{2} + \frac{A_n}{r} \right) \quad (6)$$

where  $A_n$  is the integration constant for region  $n$ . Defining  $K_n$  as the ratio of the inner boundary radius of region  $n$  to the annulus tip radius  $R_t$  and defining  $V_n$  as the velocity at the inner boundary radius of region  $n$ ,

equation (6) can be integrated from the inner boundary of region  $n$  to an arbitrary radius within the region:

$$\int_{v_n}^v dv = - \frac{1}{\mu^{(2)}(1 + m_n)} \int_{K_n R_t}^r \left( \frac{pr}{2} + \frac{A_n}{r} \right) dr \quad (7)$$

Finally for any region  $n$

$$v(r) = v_n - \frac{1}{\mu^{(2)}(1 + m_n)} \left\{ \frac{pR_t^2}{4} \left[ \left( \frac{r}{R_t} \right)^2 - K_n^2 \right] + A_n \ln \left( \frac{r}{K_n R_t} \right) \right\} \quad (8)$$

Note that  $K_1$  is equal to the hub-to-tip radius ratio and  $K_{N+1}$  is equal to 1. At the interface of two adjacent regions the solutions are "spliced" together by equating the velocity gradients. Writing equation (6) for regions  $n$  and  $n+1$  at a common radius  $K_{n+1}$  and equating the two resulting expressions yields

$$\frac{1}{1 + m_n} \left( \frac{pK_{n+1}R_t}{2} + \frac{A_n}{K_{n+1}R_t} \right) = \frac{1}{1 + m_{n+1}} \left( \frac{pK_{n+1}R_t}{2} + \frac{A_{n+1}}{K_{n+1}R_t} \right) \quad (9)$$

Solving for  $A_{n+1}$  results in a recursion relation

$$A_{n+1} = \left[ \frac{1 + m_{n+1}}{1 + m_n} \left( \frac{pK_{n+1}R_t}{2} + \frac{A_n}{K_{n+1}R_t} \right) - \frac{pK_{n+1}R_t}{2} \right] K_{n+1}R_t \quad (10)$$

Velocities at the interfaces between regions can be computed by evaluating equation (8) at  $r = K_{n+1}R_t$ :

$$v_{n+1} = v(K_{n+1}R_t) = v_n - \frac{1}{\mu^{(2)}(1 + m_n)} \left[ \frac{pR_t^2}{4} (K_{n+1}^2 - K_n^2) + A_n \ln \left( \frac{K_{n+1}}{K_n} \right) \right] \quad (11)$$

Applying the no-slip boundary condition at the tip radius  $R$ , equation (11) becomes

$$0 = v_N - \frac{1}{\mu^{(2)}(1 + m_N)} \left[ \frac{pR_t^2}{4} (K_{N+1}^2 - K_N^2) + A_N \ln \left( \frac{K_{N+1}}{K_N} \right) \right] \quad (12)$$

Now  $V_n$  can be successively replaced by using equation (11) until an equation of the form

$$\left. \begin{aligned} V_1 &= \sum_{n=1}^N F(n) \\ F(n) &= \frac{1}{\mu(l)(1+m_n)} \left[ \frac{pR_t^2}{4} (K_{n+1}^2 - K_n^2) + A_n \ln \left( \frac{K_{n+1}}{K_n} \right) \right] \end{aligned} \right\} \quad (13)$$

results. Since  $V_1$  is the velocity at the inner boundary of region 1, it is the velocity at the hub surface and is zero. Hence

$$0 = \sum_{n=1}^N F(n) \quad (14)$$

Equation (14) along with the  $N - 1$  equations obtained from the recursion relation for  $A_n$  (eq. (10)) can be arranged into the following form:

$$C_1 A_1 + C_2 A_2 + \dots + C_{N-1} A_{N-1} + C_N A_N = B \quad (14)$$

$$E_1 A_1 - A_2 = -D_1 \quad (10)$$

$$E_2 A_2 - A_3 = -D_2 \quad (10)$$

$\vdots$

$$E_{N-1} A_{N-1} - A_N = -D_{N-1} \quad (10)$$

where

$$B = - \frac{pR_t^2}{4} \sum_{n=1}^N \frac{K_{n+1}^2 - K_n^2}{1 + m_n} \quad (15)$$

$$C_n = \frac{1}{1 + m_n} \ln \left( \frac{K_{n+1}}{K_n} \right) \quad (16)$$

$$D_n = \frac{p(K_{n+1} R_t)^2}{2} \left( \frac{1 + m_{n+1}}{1 + m_n} - 1 \right) \quad (17)$$

$$E_n = \frac{1 + m_{n+1}}{1 + m_n} \quad (18)$$

Cramer's rule can be used to solve for the integration constant in region 1 ( $A_1$ ), after which repeated application of equation (10) yields all other  $A_n$ 's. The velocity profile for the entire annulus is now computed by using equation (8), beginning at the hub surface (where  $V_1 = 0$ ) and progressing to the outer radius of region 1. At the outer radius of region 1 a solution for  $V_2$  results, and equation (8) is applied again for region 2. In a similar manner the solution progresses across the annulus to the tip surface, where the no-slip boundary condition has previously been satisfied in equation (14).

Values of turbulent-to-laminar viscosity ratio  $m_n$  and region boundaries, as well as the number of regions used  $N$  in this investigation are depicted in figure 2. These constants were found to best fit available experimental velocity profile data over a wide range of hub-to-tip radius ratios with only the region 5 viscosity ratio  $m_5$  varying with hub-to-tip radius ratio. In figure 3 nondimensional velocity profiles obtained by this procedure show good agreement with the experimental data of reference 2.

### Calculation of Flow Coefficients

For the purpose of this analysis flow coefficient is defined as the ideal flow rate divided by the measured or indicated flow rate. The ideal flow rate is determined by using the semiempirical velocity profile. The indicated flow rate is determined by using an area-weighted summation of velocity values taken from the semiempirical profile at the rake probe locations. Under the assumption of incompressible flow the flow coefficient reduces to the following:

$$C_F = \frac{2 \int_{K_1}^1 v(u)u \, du}{(1 - K_1^2) \sum_{i=1}^I A_i v_i} \quad \left(u = \frac{r}{R_t}\right) \quad (19)$$

where  $v_i$  is the velocity at probe location  $i$ ,  $A_i$  is the annular area fraction associated with that probe, and  $I$  is the number of probes on the rake. If the rake is area weighted, all  $A_i$  are equal. Solutions to equation (19) were obtained by using the Fortran computer program listed in the appendix. The program evaluates the numerator by applying a sixth-order numerical integration technique known as Weddle's method to equation (8). Inputs to the program are annulus hub-to-tip ratio and the number of probes on the rake. A subroutine automatically locates the probes at area-weighted radii although provisions exist to input other rake geometries through an input data set. Turbulent-to-laminar viscosity ratios, region boundaries, and the number of regions used in conjunction with equation (8) are input through a separate input data set. All results presented were obtained by using the values in figure 2.



## RESULTS

Figure 4 depicts the differences between the ideal velocity profile and the discretized profile that is summed in obtaining the indicated flow rate. For all probes compensating errors occur. However, probes near the hub and tip surfaces will clearly overpredict the flow rate because of the no-slip condition at these surfaces. The discretized profiles more closely approximate the ideal profile as the number of probes increases. Figure 5 presents the flow coefficients obtained with the Fortran program for area-weighted rakes with one to 10 probes over a range of annulus hub-to-tip radius ratios.

## CONCLUSIONS

An investigation was conducted to determine the error in the rake mass flow rate measurement for turbulent flow in an annulus due to the discretization of the velocity profile and the variation of this error with the number of probes on an area-weighted rake. The following conclusions were drawn:

1. The semiempirical method presented for determining fully developed, turbulent velocity profiles in an annulus agreed adequately with experimental data.
2. Flow coefficients ranged from 0.903 for one probe placed at a radius dividing two equal areas to 0.984 for a 10-probe area-weighted rake.
3. Flow coefficients were not a strong function of annulus hub-to-tip radius ratio for rakes having three or more probes.

# APPENDIX - COMPUTER PROGRAM LISTING

```

0000100 C
0000200 C*****DONUT.SOURCE.TAPVA
0000300 C
0000400 C THIS PROGRAM COMPUTES SEMI-EMPIRICAL VELOCITY PROFILES FOR FULLY-DEVELOPED TURBULENT
0000500 C FLOW IN AN ANNULUS. THESE PROFILES ARE COMPARED TO DISCRETIZED PROFILES AS INDICATED
0000600 C BY A PITOT RAKE SUBJECTED TO THE SEMI-EMPIRICAL FLOW FIELD. FLOW COEFFICIENTS ARE
0000700 C CALCULATED BY DIVIDING THE 'ACTUAL' FLOWRATE BY THE INDICATED FLOWRATE. THE 'ACTUAL'
0000800 C FLOWRATE IS OBTAINED BY A NUMERICAL INTEGRATION OF THE SEMI-EMPIRICAL PROFILE. THE
0000900 C INDICATED FLOWRATE IS OBTAINED BY AN AREA-WEIGHTED SUM OF VELOCITIES OBTAINED FROM
0001000 C THE SEMI-EMPIRICAL VELOCITY PROFILE AT THE RAKE PROBE LOCATIONS. RESULTS ARE OUTPUT
0001100 C GRAPHICALLY.
0001200 C
0001300 C DOUBLE PRECISION CAPP(10),VISCO(10)
0001400 C DOUBLE PRECISION VISCOL,PRESS,RADIUS
0001500 C DOUBLE PRECISION B(10),C(10),D1,D2,D3,D(10),E(10),BSUM,ATERM,ANUM,ADEN,A(10)
0001600 C DOUBLE PRECISION V(2000),VINTER(10),RATIO,VREF,H(10),HSUB(10),VSUM,SUBSUM(10),P1,P2,P3,RV,COEFF(7)
0001700 C
0001800 C DIMENSION NINT(10),VEL(2000),RAD(2000)
0001900 C DIMENSION AREA(100),TLOC(100),DISC(100),PLOC(100),TVEL(100),PVEL(100)
0002000 C DIMENSION PFLOW(2)
0002100 C DATA COEFF/1.,5.,1.,6.,1.,5.,1./
0002200 C
0002300 C DIMENSION XVAR(10),YVAR(10)
0002400 C DIMENSION IVAR(10)
0002500 C
0002600 C
0002700 C*****INPUT REGION GEOMETRY AND FLOW VARIABLES
0002800 C
0002900 C READ(5,1000) NREG
0003000 C READ(5,1500) ALPHA
0003100 C DO 100 I=1,NREG
0003200 C READ(5,1100) CAPP(I),NINT(I),VISCO(I)
0003300 C CAPP(I)=ALPHA+(1-ALPHA)*CAPP(I)
0003400 C 100 CONTINUE
0003500 C
0003600 C READ(5,1200) VISCOL
0003700 C READ(5,1200) PRESS
0003800 C READ(5,1200) RADIUS
0003900 C
0004000 C CAPP(NREG+1)=1.
0004100 C
0004200 C
0004300 C*****COMPUTE INTEGRATION CONSTANT FOR REGION ONE
0004400 C
0004500 C DO 200 N=1,NREG
0004600 C
0004700 C B(N)=PRESS*RADIUS**2*(CAPP(N+1)**2-CAPP(N)**2)/(4*(1+VISCO(N)))
0004800 C CN=(DLOG(CAPP(N+1)/CAPP(N)))/(1+VISCO(N))
0004900 C D1=(1+VISCO(N+1))/(1+VISCO(N))
0005000 C D2=PRESS*(CAPP(N+1)**2*(RADIUS**2)/2
0005100 C D(N)=D2*(D1-1)
0005200 C E(N)=D1
0005300 C
0005400 C 200 CONTINUE
0005500 C
0005600 C
0005700 C*****SOLVE NXN MATRIX FOR A(1) AND COMPUTE REMAINING A(N)'S
0005800 C
0005900 C BSUM=0
0006000 C DO 220 I=1,NREG
0006100 C BSUM=BSUM-B(I)
0006200 C 220 CONTINUE
0006300 C
0006400 C ATERM=D(1)
0006500 C ANUM=BSUM
0006600 C DO 240 I=2,NREG
0006700 C ANUM=ANUM-C(I)*ATERM
0006800 C ATERM=ATERM*E(I)+D(I)
0006900 C 240 CONTINUE
0007000 C
0007100 C ATERM=1
0007200 C ADEN=0
0007300 C DO 260 I=1,NREG
0007400 C ADEN=ADEN+C(I)*ATERM
0007500 C ATERM=ATERM*E(I)
0007600 C 260 CONTINUE
0007700 C
0007800 C A(1)=ANUM/ADEN
0007900 C
0008000 C DO 300 N=2,NREG
0008100 C A(N)=D(N-1)+E(N-1)*A(N-1)
0008200 C 300 CONTINUE
0008300 C
0008400 C
0008500 C*****NUMERICALLY INTEGRATE VELOCITY PROFILE FROM CAPP(1) TO 1
0008600 C
0008700 C
0008800 C VSUM=0.
0008900 C VINTER(1)=0.
0009000 C JSTART=1
0009100 C
0009200 C DO 600 N=1,NREG
0009300 C

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0009400      SUBSUM(N)=0.
0009500      H(N)=(CAPPA(N+1)-CAPPA(N))/NINT(N)
0009600      HSUB(N)=H(N)/6.
0009700      RATIO=CAPPA(N)
0009800 C
0009900      NSTOP=NINT(N)
0010000      DO 500 NSUB=1,NSTOP
0010100 C
0010200      JSTOP=JSTART+6
0010300      K=1
0010400 C
0010500      DO 400 J=JSTART,JSTOP
0010600 C
0010700      P1=1./((VISCOL*(1+VISCO(N)))
0010800      P2=PRESS*RADIUS**2*(RATIO**2-CAPPA(N)**2)/4
0010900      P3=A(N)*DLOG(RATIO/CAPPA(N))
0011000      V(J)=VINTER(N)-P1*(P2+P3)
0011100      RV=V(J)*RATIO
0011200 C
0011300      RAD(J)=RATIO
0011400      SUBSUM(N)=SUBSUM(N)+COEFF(K)*RV
0011500      K=K+1
0011600      RATIO=RATIO+HSUB(N)
0011700 C
0011800      400 CONTINUE
0011900 C
0012000      RATIO=CAPPA(N)+NSUB*H(N)
0012100      JSTART=J
0012200 C
0012300      500 CONTINUE
0012400 C
0012500      SUBSUM(N)=.3*HSUB(N)*SUBSUM(N)
0012600      VSUM=VSUM+SUBSUM(N)
0012700      VINTER(N+1)=V(J)
0012800 C
0012900      600 CONTINUE
0013000 C
0013100 C
0013200 C*****COMPUTE POINT OF MAXIMUM VELOCITY (VREF), AND VAVG
0013300 C
0013400      N=(NREG+1)/2
0013500 C
0013600      RATIO=DSQRT(-2*A(N)/((PRESS*RADIUS**2))
0013700 C
0013800      P1=1./((VISCOL*(1+VISCO(N)))
0013900      P2=PRESS*RADIUS**2*(RATIO**2-CAPPA(N)**2)/4
0014000      P3=A(N)*DLOG(RATIO/CAPPA(N))
0014100      VREF=VINTER(N)-P1*(P2+P3)
0014200 C
0014300      VAVG=2*VSUM/(VREF*(1-CAPPA(1)**2))
0014400 C
0014500 C
0014600 C*****PLOT THEORETICAL PROFILE USING POINTS OF INTEGRATION
0014700 C
0014800      DO 650 I=1,JSTOP
0014900      VEL(I)=V(I)/VREF
0015000      650 CONTINUE
0015100 C
0015200      XVAR5(1)=9
0015300      XVAR5(2)=6.
0015400      XVAR5(3)=0.
0015500      XVAR5(4)=0.
0015600      XVAR5(5)=1.
0015700      XVAR5(6)=5.
0015800      XVAR5(7)=1.
0015900      XVAR5(8)=6.
0016000      XVAR5(9)=CAPPA(1)
0016100      CALL XAXIS(1.,1.,XVAR5)
0016200 C
0016300      YVAR5(1)=9
0016400      YVAR5(2)=8.
0016500      YVAR5(3)=90.
0016600      YVAR5(4)=CAPPA(1)
0016700      YVAR5(5)=1.
0016800      YVAR5(6)=5.
0016900      YVAR5(7)=1.
0017000      YVAR5(8)=2.
0017100      YVAR5(9)=0.
0017200      CALL YAXIS(1.,1.,YVAR5)
0017300 C
0017400      CALL CORNER(1)
0017500 C
0017600      IVAR5(1)=2
0017700      IVAR5(2)=JSTART
0017800 C
0017900      CALL GLOT(VEL,RAD,IVAR5)
0018000 C
0018100      CALL AVRAD(VEL,RAD,JSTART,VAVG,RADH,RADT)
0018200 C
0018300 C*****ANALYZE RAKE PROFILE
0018400 C*****INPUTS ARE NUMBER OF TUBES, RADIAL LOCATIONS
0018500 C*****AND ANNULAR AREA FRACTION ASSUMED FOR EACH TUBE
0018600 C
0018700      TSUM=0.
0018800      READ(6,1300) NTUBE
0018900 C

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0019000      DO 700 I=1,NTUBE
0019100      READ(6,1400) TLOC(I),AREA(I)
0019200      700 CONTINUE
0019300 C
0019400 C
0019500 C*****COMPUTE POINTS OF DISCONTINUITY
0019600 C
0019700      ATOT=1-CAPPA(1)**2
0019800      DISC(1)=CAPPA(1)
0019900 C
0020000      ISTOP=NTUBE+1
0020100      DO 750 I=2,ISTOP
0020200      DISC(I)=SQRT((AREA(I-1)*ATOT)+DISC(I-1)**2)
0020300      750 CONTINUE
0020400 C
0020500 C
0020600 C
0020700 C*****COMPUTE VELOCITY AT EACH TUBE LOCATION AND DO WEIGHTED SUM
0020800 C
0020900      DO 800 J=1,NTUBE
0021000 C
0021100      DO 850 N=1,NREG
0021200      IF(CAPPA(N+1).GE.TLOC(J))GO TO 875
0021300      850 CONTINUE
0021400      875 CONTINUE
0021500 C
0021600      RATIO=TLOC(J)
0021700 C
0021800      P1=1./(VISCOL*(1+VISC0(N)))
0021900      P2=PRESS*RADIUS**2*(RATIO**2-CAPPA(N)**2)/4
0022000      P3=A(N)*DLOG(RATIO/CAPPA(N))
0022100      V(J)=(VINTER(N)-P1*(P2+P3))/VREF
0022200      TSUM=TSUM+AREA(J)*V(J)
0022300 C
0022400      800 CONTINUE
0022500 C
0022600 C
0022700 C*****COMPUTE FLOW COEFFICIENT
0022800 C
0022900      CFLOW=VAVG/TSUM
0023000 C
0023100 C
0023200 C*****PLOT 'ASSUMED' PROFILE, WITH TUBE LOCATIONS
0023300 C
0023400      NPOINT=NTUBE*2
0023500 C
0023600      DO 900 I=1,NTUBE
0023700      II=I*2
0023800      PVEL(II)=V(I)
0023900      PVEL(II-1)=V(I)
0024000      900 CONTINUE
0024100 C
0024200      PLOC(1)=CAPPA(1)
0024300      DO 950 I=1,NTUBE
0024400      II=I*2
0024500      PLOC(II)=DISC(I+1)
0024600      PLOC(II+1)=DISC(I+1)
0024700      950 CONTINUE
0024800 C
0024900      IVARS(2)=NPOINT
0025000 C
0025100      CALL GLOT(PVEL,PLOC,IVARS)
0025200 C
0025300 C
0025400      DO 975 I=1,NTUBE
0025500      TVEL(I)=V(I)
0025600      975 CONTINUE
0025700 C
0025800      IVARS(1)=6
0025900      IVARS(2)=NTUBE
0026000      IVARS(3)=3
0026100      IVARS(4)=62
0026200      IVARS(5)=1
0026300      IVARS(6)=20
0026400 C
0026500      CALL GLOT(TVEL,TLOC,IVARS)
0026600 C
0026700 C
0026800      CALL NUMBER(4,CFLOW,6,4,PFLOW)
0026900      CALL CHARS(6,PFLOW,0,4.8,.5,15)
0027000      CALL CHARS(12,'FLOW COEFF =',0,3...5,15)
0027100 C
0027200      PRINT1500,CFLOW
0027300      CALL DISPLA(1)
0027400 C
0027500      STOP
0027600 C
0027700 C
0027800 C*****FORMATS
0027900 C
0028000      1000 FORMAT(I2)
0028100      1100 FORMAT(F6.4,2X,I2,2X,F10.5)
0028200      1200 FORMAT(D11.4)
0028300      1300 FORMAT(I3)
0028400      1400 FORMAT(F10.5,2X,F10.5)
0028500      1500 FORMAT(F10.5)
0028600 C
0028700      END

```

#### REFERENCES

1. Sanders, Bobby W.: Dynamic Response of a Mach 2.5 Axisymmetric Inlet and Turbojet Engine with a Poppet-Valve-Controlled Inlet-Stability Bypass System when Subjected to Internal and External Airflow Transients. NASA TP-1531, 1980.
2. Brighton, J.A.; and Jones, J.B.: Fully Developed Turbulent Flow in Annuli. J. Basic Eng., vol. 86, no. 4, Dec. 1964, pp. 835-844.

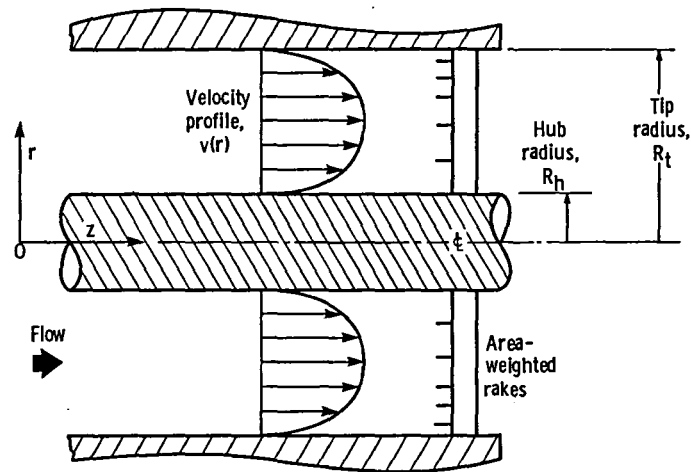
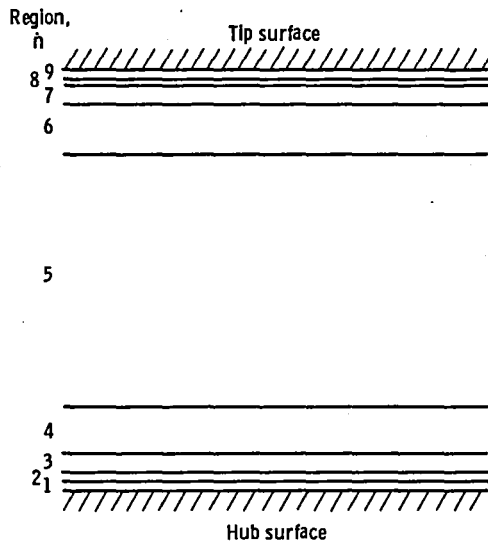


Figure 1. - Annulus nomenclature and coordinate system.



Region, $n$	Dimensionless distance from hub surface to inner radius of region $n$ , $K'_n$	Ratio of turbulent to laminar viscosity in region $n$ , $m_n$
9	0.978	0
8	.965	5
7	.920	75
6	.800	400
5	.200	See plot
4	.090	500
3	.045	100
2	.022	10
1	0	0

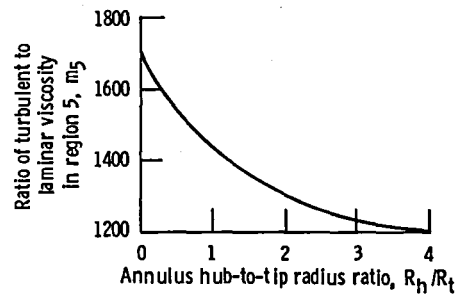


Figure 2. - Annular region geometry and turbulent-to-laminar viscosity ratios used in semiempirical scheme.

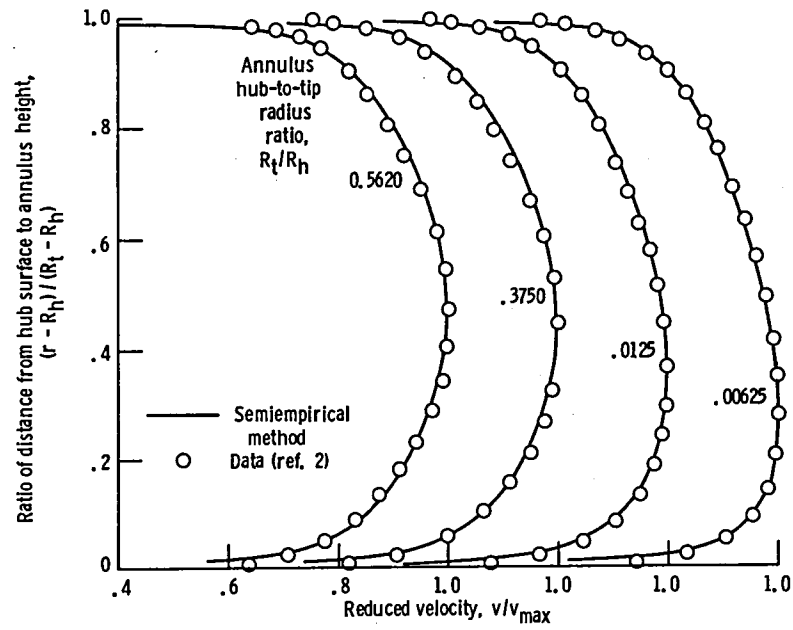
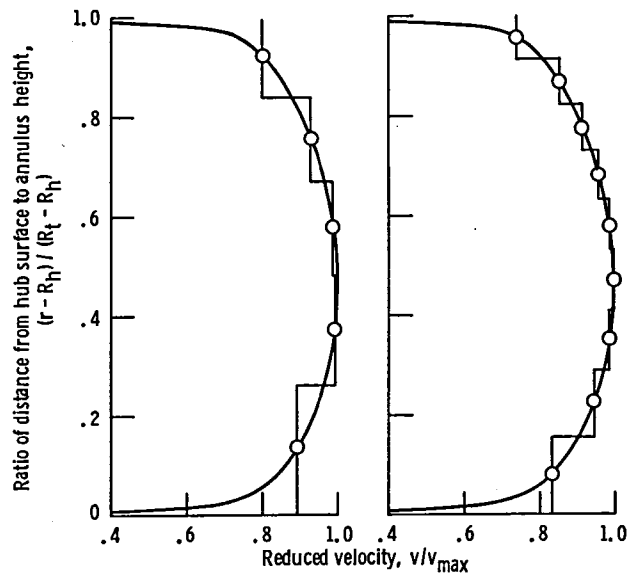


Figure 3. - Comparison of semiempirical velocity profiles with experimental data of reference 2.



(a) Five-probe rake. Flow coefficient,  $C_F$ , 0.9771.

(b) Nine-probe rake. Flow coefficient,  $C_F$ , 0.9834.

Figure 4. - Comparison of discretized velocity profiles with "actual" profiles for five- and nine-probe rakes.

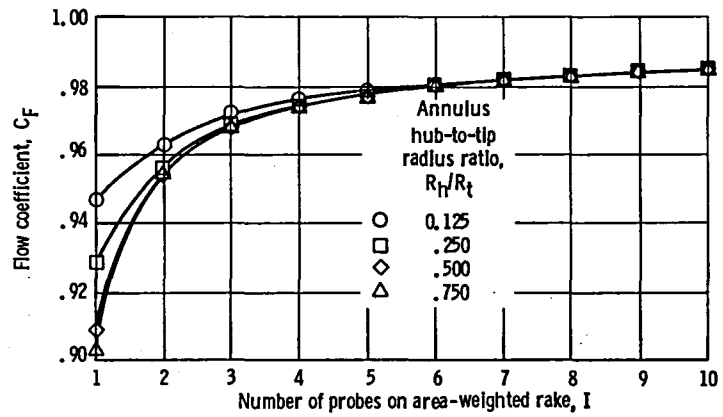


Figure 5. - Flow coefficient as function of number of probes on area-weighted rake.



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4. Title and Subtitle  <b>Semiempirical Method of Determining Flow Coefficients for Pitot Rake Mass Flow Rate Measurements</b>				5. Report Date <b>November 1985</b>	
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15. Supplementary Notes					
16. Abstract  Flow coefficients applicable to area-weighted pitot rake mass flow rate measurements are presented for fully developed, turbulent flow in an annulus. A turbulent velocity profile is generated semiempirically for a given annulus hub-to-tip radius ratio and integrated numerically to determine the ideal mass flow rate. The calculated velocities at each probe location are then summed, and the flow rate as indicated by the rake is obtained. The flow coefficient to be used with the particular rake geometry is subsequently obtained by dividing the ideal flow rate by the rake-indicated flow rate. Flow coefficients ranged from 0.903 for one probe placed at a radius dividing two equal areas to 0.984 for a 10-probe area-weighted rake. Flow coefficients were not a strong function of annulus hub-to-tip radius ratio for rakes with three or more probes. The semiempirical method used to generate the turbulent velocity profiles is described in detail.					
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